Trip Times Investigation of Ground Fault Circuit Interrupter

M. Rabiul Alam, Rajib Baran Roy, Md. Minhaj-Us-Shiraj, H.M. Mahadi Hasan

Abstract—The objective of this study is to ascertain the capabilities and limitations of the Ground Fault Circuit Interrupters (GFCI). A GFCI is an electrical device which is designed to protect people from electric shock. GFCI protection devices are installed as per current requirements, including all wet areas that may have potential for electrical shock. The GFCI continually matches the amount of current going to an electrical device against the amount of current returning from the device along the electrical path. It senses small imbalances in the circuit in the range of approximately 5 mA and turns off all power by tripping a delay circuit in the GFCI within 36.3s and thereby protecting the load. The most efficient trip times are found 123.2s and 155.1s which will also protect the load very safely.

Index Term—Electric shock, GFCI, Receptacle, On-delay, Time delay

I. INTRODUCTION

Every year many people are shocked by electricity and sometimes it also causes death. An electric shock can occur upon contact of a human or animal body with any source of voltage high enough to cause sufficient current flow through the muscles or nerves. The minimum detectable current in humans is thought to be about 1 mA [9]. Exposure to currents as low of 100 mA for only two seconds can cause death and larger current can cause death in much shorter times. Low voltage electricity (less than 500 volts) does not normally cause significant injury to humans. Exposure to high voltage electricity (greater than 500 volts) has the potential to result in serious damage [13]. Such an accidental connection between a power system conductor and the earth is called a ground fault. Ground faults may be caused by many things, including dirt buildup on power line insulators (creating a dirty-water path for current from the conductor to the pole, and to the ground, when it rains), ground water infiltration in buried power line conductors, and birds landing on power lines, bridging the line to the pole with their wings [14].

Ground Fault Circuit Interrupter (GFCI) protects from electrical shock by interrupting a household circuit when there is a difference in the currents in the "hot" and neutral wires. Such a difference indicates that an abnormal diversion of current from the "hot" wire is occurring. And that a current might be flowing in the ground wire, such as a leakage current from a motor or from capacitors. More importantly, that current diversion may be occurring because a person has met the "hot" wire and is being shocked. When a circuit is functioning normally, all the return current from an appliance flows through the neutral wire, so the presence of a difference between "hot" and neutral currents represents a malfunction which in some circumstances could produce a dangerous or even lethal shock hazard [11]. The GFCI has been designed to detect currents of a few milliamperes and trip a breaker at the receptacle or at the breaker panel to remove the shock hazard.

II. GROUND FAULT CIRCUIT INTERRUPTER

A Ground Fault Circuit Interrupter (GFCI) is an automatic device that offers personal protection against electric shock. They are installed in areas where known electric shock hazards exist outdoor outlets and fixtures, swimming pools, saunas and hot tubs, outlets in kitchens, basements, bathrooms, and garages. Wherever there is the potential for contact between a person and an electrical appliance, a GFCI should be protecting the circuit. Becoming more advanced and safer over a few decades of existence, these inexpensive GFCI outlets are currently protecting lives in various locations in the properties [14].

A. Electrical Hazards

The major hazards associated with electricity are electric shock and fire. Electric shock occurs either when an individual comes in contact with both wires of an electrical circuit or a metallic part that has become energized by contact with an electrical conductor. The table 1 shows the general relationship between the degree of injury and amount of current for a 60-cycle hand-to-foot path of one second's duration of shock [11, 17].

<table>
<thead>
<tr>
<th>Current</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mA</td>
<td>Perception level</td>
</tr>
<tr>
<td>5 mA</td>
<td>Slight shock felt, not painful but disturbing</td>
</tr>
<tr>
<td>6-16 mA</td>
<td>Painful shock, begin to lose muscular control</td>
</tr>
<tr>
<td>17-99 mA</td>
<td>Extreme pain, severe muscular contractions</td>
</tr>
<tr>
<td>4+ A</td>
<td>Heart paralysis and severe burns. Death is probable</td>
</tr>
</tbody>
</table>

B. The Purpose of GFCI

The main purpose of GFCI is Personal safety and Property safety [6].

Personal Safety. GFCIs help keep people safe from electrical shocks, which can range from a very minor pain to electrocution. When a GFCI cuts power, the short (ground fault) has already occurred, but often the person is saved from serious injury.

Property Safety. A GFCI prevents many dangers by stopping the flow of electricity before it can do significant
damage. An unprotected short almost always damages the object the electricity passes through, and it can even cause an electrical fire.

C. Classification of GFCI

Three common types of GFCI are available for home [7]: Receptacle type, Circuit breaker type and Portable type. All three types perform the same function though each has different applications and limitations.

Receptacle Type. This type of GFCI is used in place of the standard duplex receptacle found throughout the house. It fits into the standard outlet box and protects against “ground faults” whenever an electrical product is plugged into the outlet. Most receptacle type GFCIs can be installed so that they also protect other electrical outlets further “downstream” in the branch circuit. The figure 1 shows a receptacle type GFCI outlet.

Circuit Breaker Type. The circuit breaker GFCI serves a dual purpose - not only will it shut off electricity in the event of a “ground fault,” but it will also trip when a short circuit or an overload occurs. Protection covers the wiring and each outlet, lighting fixture, heater, etc. served by the branch circuit protected by the GFCI in the panel box. The figure 2 shows a circuit breaker type GFCI outlet.

Portable Type. Where permanent GFCIs are not practical, portable GFCIs may be used. Portable GFCIs should only be used on a temporary basis and should be tested prior to every use. One type contains the GFCI circuitry in a plastic enclosure with plug blades in the back and receptacle slots in the front which can be plugged into a receptacle, and then the electrical product is plugged into the GFCI. Another type of portable GFCI is an extension cord combined with a GFCI which adds flexibility in using receptacles that are not protected by GFCIs. The figure 3 shows a portable type GFCI outlet.

D. Basic Working Principle of GFCI

In a typical 2-wire circuit, the current returning to the power supply will be equal to the current leaving the power supply (except for some small leakage). If the difference between the current leaving and returning through the current transformer of the GFCI protection device exceeds 5 mA, the solid-state circuitry opens the switching contacts and de-energizes the circuit. This will always happen as long as the GFCI is in working order. However, when a GFCI protection device fails, the switching contacts remain closed, and the device continues to provide power but no protection. The figure 4 shows the block-diagram of a GFCI outlet [8]. If the sensed current is above a predetermined level then it is detected through an op-amp comparator. The voltage in the sensor coil is rectified and applied to the input of the sensitive comparator. The comparator activates a trip coil and opens both the “hot” and neutral wires and sends a signal to the relay circuit which causes the contacts to open or “trip”.

Styles of Tripping Times. There is two basic styles of tripping times [12]: Instantaneous and Delay tripping. Instantaneous tripping time means that when the GFCI senses an imbalance, it trips as soon as possible. Delayed tripping time is when the GFCI senses in imbalance, it starts a timer and if the imbalance still exists when the time is up the GFCI will trip. The higher the imbalance the faster is the trip. When a current imbalance occurs, the magnetic field induced in the core causes an electric current. That current triggers the relay that can be used to cut off the power to the damaged appliance and prevent serious shock.

GFCI Testing. GFCI outlets should be tested periodically, at least once a year. A GFCI outlet has a “Test” and a “Reset” button. Pressing the “Test” button will trip the outlet and break the circuit. Pressing the “Reset” will restore the circuit. If pressing the test button does not work, then replace the GFCI outlet. If the outlet does pop when press the “Test” button, but the outlet still has power, the outlet is miswired. A miswired outlet is dangerous and it should be fixed immediately. Some models of GFCI have a status light to indicate whether the outlet has power, some use the indicator light to identify a problem such as being miswired. A green light indicates correct wiring and/or the outlet has power. Because there is no standard though, other indicators are open to interpretation depending on brand and year of manufacture [9].

E. GFCI Limitation

GFCI circuitry has certain inherent limitations that will cause them to open the circuit inappropriately. These conditions are called Capacitive coupling and Spurious signals [10].

Capacitive Coupling. It occurs when long cables are buried in the earth and the top and bottom parts of the cable act like the plates of a capacitor. This allows tiny current leaks to occur along the length of the cable which can open the GFCI. This is one reason that it is advantageous to locate the GFCI as close as possible to the electrical load.

Spurious Signals. It occurs when the electrical load of a circuit is changed suddenly due to turning on or off various electrical devices. The sudden change unbalances the current input and output and the GFCI trips.

F. Applications of GFCI Circuit

Basic circuit breakers are used to detect a circuit overload and automatically “trip” or shut off in order to protect the electrical system. Ground fault circuit interrupter (GFCI) circuit breakers go one step further to detect problems due to electricity being “grounded” by something that's not part of the electrical system. A GFCI circuit breaker is used in wet areas such as bathrooms, kitchens, laundry rooms, garages, outside, etc. GFCI receptacle in or around home identified the locations. Table 2 shows the most common locations, others less common are identified including laundry rooms, basements (finished), and living room is 9%. Table II

### III. CONFIGURATION AND CHARACTERISTICS OF GFCI EQUIPMENTS

A GFCI receptacle replaces a traditional electrical socket in areas where exposure to water is a concern. These receptacle is used in these types of locations is that they feature a self-tripping mechanism that immediately interrupts the power in the event of a current leak.
A. Components for Constructing the GFCI

In the receptacle outlet various electrical equipments are used and the main operating devices in a GFCI circuit are: LM324; LM555; MOC3041; Current transformer and Sensor series; BTA16.

LM324. LM324 is a low power quad operational amplifier that has been designed specifically to operate from a single power supply over a wide range of voltages [19].

LM555. The LM555 is a highly stable device for generating accurate time delays or oscillation. MOC3041. It is a zero crossing circuit (also known as optocoupler or refer to as optoisolator) allows two circuits to exchange signals yet remain electrically isolated [20].

Current Transformer and Sensor Series. A current transformer (CT) is used for measurement of electric current with different kinds of magnetic core.

BTA16. BTA16 is a DIAC (diode for alternating current) circuit - it is a trigger diode that conducts current only after its breakdown voltage has been exceeded momentarily [22].

These equipments are the main operating device in a GFCI circuit. The configuration and characteristics of some of these equipments are briefly discussed here.

B. Analysis of LM555

The 8-pin LM555 timer is one of the most useful ICs ever made and it is used in many projects. With just a few external components it can be used to build many circuits, not all of them involving timing. It comes in a single or dual package. Common part numbers are LM555, NE555, LM556, and NE556. The LM555 timer consists of two voltage comparators, a bi-stable flip-flop, a discharge transistor, and a resistor divider network. The LM555 is a highly stable device for generating accurate time delays or oscillation. The LM555 has three operating modes: Monostable, Astable and Bistable mode or Schmitt trigger [18].

Monostable Mode. In this mode the LM555 functions as a “one-shot” pulse generator. Applications include timers, missing pulse detection, bounce free switches, touch switches, frequency divider, capacitance measurement, pulse-width modulation (PWM), etc.

Astable Mode. The LM555 can operate as an oscillator. Uses include LED and lamp flashers, pulse generation, logic clocks, tone generation, security alarms, pulse position modulation, etc. Selecting a thermostat as timing resistor allows the use of the LM555 in a temperature sensor. The use of a microprocessor based circuit can then convert the pulse period to temperature, liberalize it and even provide calibration means.

Bistable Mode or Schmitt Trigger. The LM555 can operate as a flip-flop, if the DIS pin is not connected and no capacitor is used. Uses include bounce-free latched switches. Applications include precision timing, pulse generation, sequential timing, time delay generation and pulse-width modulation (PWM), etc.

Pin Configuration of LM555

The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. When the timer is operated as monostable (one-shot) multivibrator, the output voltage is low until a negative going trigger pulse is applied to the timer; and then the output switches high [2].

On-Delay Timer Circuit

There are two types of timing events that may be required during a power-on application. It can apply power to one part of a system and wait for a short interval before starting some other part of the system. In the circuit power is applied to a system when the switch is closed. The LM555’s output goes high for a period of time T and then goes low. T is found from the equation, \( T_{\text{high}} = 1.1R_C C \). This type of startup pulse is typically used to reset counters and initialize computer sequences after a power failure. It can also allow time before arming an alarm system so that an operator can exit after the system has turned on. The figure 5 shows the on-delay timing output curve of LM555 timer circuit [5] (VO goes high for a time interval T after power is applied).

Monostable Mode of Operation

This circuit is configured in monostable mode of operation which is a basic time delay circuit using a LM555 type of timer. It is also referred to as a one-shot circuit as it generates one fixed delay pulse every time it is triggered. The figure 6 shows the characteristics curve of LM555 according to monostable mode of operation [4].

C. Analysis of Current Transformers and Sensor Series

Current transformers for net frequencies of 50/60 Hz have designed with different kinds of magnetic cores. One kind is iron-steel laminations which is able to measure currents up to 600 or 700A [21] at this frequency range. Other kind of cores as for example, nanocrystalline and amorphous cores, makes it possible to get more measurement accuracy (they are not suitable to measure high levels of current up to 100A). These low frequency transformers can carry in some cases levels of DC current without saturation of the core [3].

Shunt Resistor

Shunt resistors are the simplest way to measure current. The principle to measure current is based in a serial connection of a resistance. It is preferable to have very low tolerance to allow current flowing through resistor to measure it. Variations in the current will be detected as variations of voltage in the Shunt [3].

IV. SIMULATION AND OPERATION OF GFCI

Minimum ground fault protection can be incorporated into the main power disconnect device and could be considered adequate for the entire system. A GFCI measures the current difference between the hot and neutral wires and if an imbalance occurs, the GFCI immediately cuts off the electricity. Highly inductive loads like large motors or even fluorescent lamps or fixtures on the same circuit can cause nuisance tripping of GFCIs. GFCI devices intended to protect people to interrupt the circuit if the leakage current exceeds a range of 4–6 mA (the trip setting is typically 5 mA) within 25 ms. GFCIs always tripped at 5-6 mA and after tripping a time-delay time is created.

A. Calculation of Delay Time

A time delay circuit is a programmable circuit that provides a delay in signal. A simple way to add switch on and turn-off delay to an LED circuit is to connect a resistor and capacitor in series to form an RC circuit [6]. The LM555 timer is one of the most successful integrated circuits (IC) which is used to find a time delay. In this circuit design the calculation of delay time is according to monostable mode of operation which produces an output pulse of fixed duration.
each time the input circuit is triggered. In this mode, one external resistor and one capacitor control the time delay. The time delay can be calculated with the equation [4],

\[ T = \frac{1}{f} \times R \times C \]

where: \( T \) is in seconds, \( R \) is in Ohms, \( C \) is in Farads

**B. Operation of Delay Circuit**

The test result presented in this work is related only to the simulation of LM555 delay circuit (using Proteus Version 12.0.0.58855). The result shall state the delay time in the process of on-delay operation. The on-delay operation is to give output when preset time expires after a predetermined input is given to the power supply circuit or input circuit [4]. The output pulse ends when the voltage on the capacitor equals 2/3 of the supply voltage. The output pulse width can be lengthened or shortened to the need of the specific application by adjusting the values of \( R \) and \( C \) [18].

**C. Simulation of Delay Circuit**

LM555 timer circuits are used in GFCI receptacle outlet and control the intermittent operation of circuits and equipment (time ON vs. time OFF). It is a highly stable integrated circuit capable of working as an accurate time delay generator and as a free running multivibrator. A monostable is said to have a single stable state and whenever it is triggered by an input pulse, the monostable switches to its temporary state. It remains in that state for a period determined by an RC network and then returns to its stable state. The trigger input is initially high (about 1/3 of \(+V\)). In this circuit, when it is simulated a negative pulse applied at pin 2 triggers an internal flip-flop that turns off pin 7's discharge transistor, allowing \( C1 \) to charge up through \( R1 \). At the same time, the flip-flop brings the output (pin 3) level to 'high'. When capacitor \( C1 \) as charged up to about 2/3 \( Vcc \), the flip-flop is triggered once again, this time making the pin 3 output 'low' and turning on pin 7's discharge transistor which discharges \( C1 \) to ground [18]. The figure 7 shows the simulation of delay circuit at monostable mode in GFCI.

After simulation, according to the above equation, the duration of the output pulse in seconds is approximately equal to,

\[ T = \frac{1}{f} \times R \times C = \frac{1.1 \times 100k \Omega \times 330 \mu F}{1000} = 36.3 \text{s} \]

To achieve long output times electrolytic capacitors are used for \( C1 \) and the value of \( R1 \) may be as high. However, with high resistance values for \( R1 \) the leakage current of the \( C1 \) becomes a significant factor in the operation of the timer. The table 3 summarizes the delay time calculation in GFCI circuit and the figure 8 shows the different time delay curves at different time interval in GFCI simulation circuit.

**Table III**

<table>
<thead>
<tr>
<th>Resistor, ( R(\text{k}\Omega) )</th>
<th>Capacitor, ( C(\mu\text{F}) )</th>
<th>Calculated Time Delay, ( T(\text{s}) )</th>
<th>Simulated Time Delay, ( T(\text{s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>560 k</td>
<td>2.2</td>
<td>1.355</td>
<td>1.33</td>
</tr>
<tr>
<td>100 k</td>
<td>330</td>
<td>36.3</td>
<td>36.1</td>
</tr>
<tr>
<td>200 k</td>
<td>560</td>
<td>123.2</td>
<td>60.0</td>
</tr>
<tr>
<td>300 k</td>
<td>470</td>
<td>155.1</td>
<td>80.0</td>
</tr>
</tbody>
</table>

On-time delay, formula determines the allowable time to operate the trip device in the GFCI. The operating time varies with the fault current level. At 5 mA of fault current, this is above the perception level. The allowable time in which may get shock before the GFCI interrupts the circuit is 36.3s.

**V. DESIGN OF GFCI CIRCUIT**

The GFCI is designed to be built into the electrical circuit to detect the difference between a system’s grounded and ungrounded conductors. The GFCI is rated to trip quickly enough to prevent an electrical incident. If the grounding conductor is not intact or low-impedance, the GFCI may not trip until a person provides a path. In this case, the person will receive a shock, but the GFCI should trip so quickly that the shock will not be harmful [16]. The figure 9 shows the overall schematic design of GFCI circuit.

A current transformer within the GFCI senses the difference in amperes. Since the line and neutral wires pass through the centre of the sense transformer, only the differential primary current is transferred to the secondary. Assuming the turn’s ratio is 1:1000, the secondary current is 1/1000th the fault current. The operational amplifier converts the secondary current to a voltage. If the fault current exceeds \( \pm 5 \text{mA} \), the devices will initiate the opening of the GFCI switching contacts and de-energize the electrical circuit. Then the operational amplifier sends a current pulse to the gate of the delay circuit [24]. When this pulse is sent to an on-delay timer within the ground fault circuit interrupter, it is immediately tripped to an open condition, and thereby opening both sides of the line and removing all power from the load. The remaining time when GFCI can shut down a circuit within 36.3s, helping prevent serious electrical shocks.

**VI. CONCLUSION**

Basic circuit breakers are used to detect a circuit overload and automatically “trip” or shut off in order to protect the electrical system. Ground Fault Circuit Interrupter (GFCI) goes one step further to detect problems due to electricity being "grounded" by something that's not part of the electrical system. A Ground Fault Circuit Interrupter is an automatic device that offers personal protection against electric shock. The GFCI prevents many dangers by stopping the flow of electricity before it can do significant damage. Wherever there is the potential for contact between a person and an electrical appliance, a GFCI should be protecting the circuit. GFCI protection devices are installed as per current requirements, including all wet areas such as bathrooms, kitchens, laundry rooms, garages, outside, etc. The GFCI is rated to trip quickly enough to prevent an electrical incident. The allowable time to operate the trip device in the GFCI varies with the fault current level. At 5 mA of fault current, this is above the perception level. The allowable time in which may get shock before the GFCI interrupts the circuit is 36.3s. In this work the delay time calculation of GFCI circuit is found that the most efficient trip times are 123.2s and 155.1s.

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REFERENCES


[23] www.national.com


Fig. 1. Receptacle type GFCI outlet

Fig. 2. Circuit breaker type GFCI outlet

Fig. 3. Portable type GFCI outlet

Fig. 4. Block-diagram of a GFCI receptacle

Fig. 5. On-delay timing output curve of LM555 timer circuit

Fig. 6. Characteristics curve of LM555 at Monostable mode of operation
Fig. 7. Simulation of delay circuit at monostable mode

a. Time delay at 1.33 sec

b. Time delay at 36.1 sec

c. Time delay at 60.0 sec

d. Time delay at 80.0 sec

Fig. 8. Time delay curves at different time interval in simulation circuit
M. Rabiul Alam received his M.S. in Electrical Engineering (1995) and awarded Ph.D. (2004) and completed a two years Postdoc in Energy Management (2006) from Moscow State Mining University, Moscow, Russia.

M. Rabiul Alam is an Associate Professor and Head of the Department of Electrical and Electronic Engineering at Hamdard University Bangladesh from 2012. During 2008 - 2012 M. Rabiul Alam was an Associate Professor and Head of the Department of Electrical and Electronic Engineering and Dean of the School of Computer Science and Engineering at University of Information Technology and Sciences (UIT), Dhaka, Bangladesh. During 2007-2008 he was an Associate Professor of the Department of Electrical and Electronic Engineering at International University of Business Agriculture and Technology (IUBAT), Dhaka, Bangladesh. His field of interest is: Power Engineering, Renewable Energy and Energy Management.

Rajib Baran Roy obtained his B.Sc. in Electrical and Electronic Engineering (2001) from Chittagong University of Engineering and Technology, Bangladesh and M.S.E.E (2008) from Flensburg University, Germany.

Rajib Baran Roy is an Assistant Professor of the Department of Electrical and Electronic Engineering at University of Information Technology and Sciences (UIT), Dhaka, Bangladesh from 2008. During 2008 - 2010 he was a Lecturer of the Department of Electrical and Electronic Engineering Department at the same University. During 2001 - 2005 he worked in the Local Government and Engineering Department, Government of Bangladesh. His field of interest is: Industrial and Power Engineering, Renewable Energy and Energy Management.

Md. Minhaj-Us-Shiraj completed his B.Sc. in Electrical and Electronic Engineering (2012) from University of Information Technology and Sciences (UIT), Dhaka, Bangladesh.

Md. Minhaj-Us-Shiraj is a Project Engineer with Siemens Aktiengesellschaft (AG) Branch Office, Dhaka, Bangladesh. His field of interest is: Industrial and Power Engineering, Electric Drives and Automation.

H.M. Mahadi Hasan completed his B.Sc. in Electrical and Electronic Engineering (2012) from University of Information Technology and Sciences (UIT), Dhaka, Bangladesh.

H.M. Mahadi Hasan is a System Engineer with Network Operation Centre (NOC), PARADISE TELECOM, Dhaka, Bangladesh. His field of interest is: Communication Engineering, Information Technology and Networking.